

High- p_T Direct Photon Azimuthal Correlation Measurements

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Abstract

The azimuthal correlations of direct photons (γ_{dir}) with high transverse momentum (p_T), produced at mid-rapidity ($|\eta^{y_{dir}}| < 1$) in Au+Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV, are measured and compared to those of neutral pions (π^0) in the same kinematic range. The measured azimuthal elliptic anisotropy of direct photon, $v_2^{y_{dir}}(p_T)$, at high p_T ($8 < p_T^{y_{dir}} < 20$ GeV/c) is found to be smaller than that of π^0 and consistent with zero when using the forward detectors ($2.4 < |\eta| < 4.0$) in reconstructing the event plane. The associated charged hadron spectra recoiled from γ_{dir} show more suppression than those recoiled from π^0 ($I_{AA}^{\gamma_{dir}-h^\pm} < I_{AA}^{\pi^0-h^\pm}$) in the new measured kinematic range $12 < p_T^{y_{dir}, \pi^0} < 24$ GeV/c and $3 < p_T^{assoc} < 24$ GeV/c.

Keywords: Electromagnetic probes, high- p_T direct photons, STAR

1. Introduction

A major goal of measurements at the Relativistic Heavy Ion Collider (RHIC) is to quantify the properties of the QCD matter created in heavy-ion collisions at high energy [1]. Unlike quarks and gluons, photons do not fragment into hadrons and can be directly observed as a final state particle. Furthermore, due to their negligible coupling to the QCD matter in contrast to hadrons, direct photons are considered as a calibrated probe for the QCD medium.

The previous measurements at RHIC indicate unexpected finite values of azimuthal elliptic anisotropy parameter v_2 of charged hadrons at high- p_T [2]. The measured v_2 at high- p_T is beyond the applicability of hydrodynamic models, and the path-length dependence of jet quenching is the only proposed explanation of v_2 at high- p_T [3]. The $v_2^{y_{dir}}$ measurement would provide a gauge for the energy loss at high- p_T .

The high- p_T γ_{dir} sample unbiased spatial distribution of the hard scattering vertices in the QCD medium [4], in contrast to hadrons which suffer from the geometric biases. Therefore, a comparison between the spectra of the away-side charged hadrons associated with γ_{dir} vs. π^0 can provide a benchmark for the energy loss and its dependence on the path-length. Although the previous measurements have indicated similar level and pattern of suppression for the away-side of γ_{dir} and π^0 [5], the current work explores a softer region in the fragmentation functions where a more significant difference is expected [6].

2. Analysis and Results

2.1. Electromagnetic neutral clusters

The STAR detector is well suited for measuring azimuthal angular correlations due to the large coverage in pseudorapidity and full coverage in azimuth (ϕ). While the Barrel Electromagnetic Calorimeter (BEMC) [7] measures

¹ A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

the electromagnetic energy with high resolution, the Barrel Shower Maximum Detector (BSMD) provides fine spatial resolution and enhances the rejection power for the hadrons. The Time Projection Chamber (TPC: $|\eta| < 1$) [8] identifies charged particles, measures their momenta, and allows for a charged-particle veto cut with the BEMC matching. The Forward Time Projection Chamber (FTPC: $2.4 < |\eta| < 4.0$) [9] is used to measure the charged particles' momenta and to reconstruct the event plane angle. Using the BEMC to select events (*i.e.* “trigger”) with high- p_T γ , the STAR experiment collected an integrated luminosity of 23 pb^{-1} of p+p collisions in 2009 and $973 \mu\text{b}^{-1}$ of Au+Au collisions in 2011. In this analysis, events having a primary vertex within $\pm 55 \text{ cm}$ of the center of the TPC along the beamline in Au+Au and $\pm 80 \text{ cm}$ in p+p are selected. In addition, each event must have at least one electromagnetic cluster with $E_T > 8 \text{ GeV}$ for the event plane correlation analysis and $E_T > 12 \text{ GeV}$ for the charged hadron correlation analysis. More than 97% of these clusters have deposited energy greater than 0.5 GeV in each layer of the BSMD. A trigger tower is rejected if it has a track with $p > 3.0 \text{ GeV}/c$ pointing to it, which reduces the number of the electromagnetic clusters by only $\sim 7\%$.

2.2. v_2 of neutral particles

The v_2 is determined using the standard method [10]:

$$v_2(p_T) = \langle \langle \cos 2(\phi_{p_T} - \psi_{\text{EP}}) \rangle \rangle, \quad (1)$$

where the brackets denote statistical averaging over particles and events, ϕ_{p_T} is the azimuthal angle of the neutral particle with certain value of p_T , and ψ_{EP} is the azimuthal angle of the event plane. The event plane is reconstructed from charged particles, within the detector acceptance, with $p_T < 2 \text{ GeV}/c$, and determined by

$$\psi_{\text{EP}} = \frac{1}{2} \tan^{-1} \left(\frac{\sum_i \sin(2\phi_i)}{\sum_i \cos(2\phi_i)} \right), \quad (2)$$

where ϕ_i are the azimuthal angles of all the particles used to define the event plane. In this analysis, the charged-track quality criteria are similar to those used in previous STAR analyses [11]. The event plane is measured using two different detectors in their pseudorapidity coverage: 1) using all the selected tracks inside the TPC, and 2) using all tracks inside the FTPC in order to reduce the “non-flow” contributions (azimuthal correlations not related to the event plane). Since the event plane is only an approximation to the true reaction plane, the observed correlation is divided by the event plane resolution. The event plane resolution is estimated using the sub-event method in which the full event is divided up randomly into two sub-events as described in [10]. Biases due to the non-uniform acceptance of the detector are removed according to the method in [12].

2.3. Azimuthal correlations of a neutral trigger particle with charged hadrons

The azimuthal correlations of a neutral trigger particle with charged hadrons, measured as the number of associated particles per neutral cluster per $\Delta\phi$ (“correlation functions”), are used in both p+p and Au+Au collisions to determine the (jet) associated particle yields in the near- ($\Delta\phi \sim 0$) and away-sides ($\Delta\phi \sim \pi$). The near- and away-side yields, Y^n and Y^a , of associated particles per trigger are extracted by integrating the $(1/N_{\text{trig}})dN/d(\Delta\phi)$ distributions over $|\Delta\phi| \leq 0.63$ and $|\Delta\phi - \pi| \leq 0.63$, respectively. The yield is corrected for the tracking efficiency of charged particles as a function of event multiplicity.

2.4. Transverse shower profile analysis

A crucial part of the analysis is to discriminate between showers from γ_{dir} and two close γ 's from high- p_T π^0 symmetric decays. At $p_T^{\pi^0} \sim 8 \text{ GeV}/c$, the angular separation between the two γ 's resulting from a π^0 decay is small, but a π^0 shower is generally broader than a single γ shower. The BSMD is capable of $2\gamma/1\gamma$ separation up to $p_T^{\pi^0} \sim 24 \text{ GeV}/c$ due to its high granularity ($\Delta\eta \sim 0.007$, $\Delta\phi \sim 0.007$). The shower shape is quantified as the cluster energy, measured by the BEMC, normalized by the position-weighted energy moment, measured by the BSMD strips [5]. The shower profile cuts were tuned to obtain a nearly γ_{dir} -free (π_{rich}^0) sample and a sample rich in γ_{dir} (γ_{rich}). Since the shower-shape analysis is only effective for rejecting two close γ showers, the γ_{rich} sample contains a mixture of direct photons and contamination from fragmentation photons (γ_{frag}) and photons from asymmetric hadron (π^0 and η) decays.

The $v_2^{\gamma_{\text{rich}}}$ and $v_2^{\pi^0}$ are measured as discussed in section 2.2 and the away (near)-side yields of associated particles per γ_{rich} and π_{rich}^0 triggers ($Y_{\gamma_{\text{rich}}+h}^{a(n)}$ and $Y_{\pi_{\text{rich}}^0+h}^{a(n)}$) are measured as discussed in section 2.3.

2.5. v_2 of direct photons

Assuming zero near-side yield for γ_{dir} triggers and a sample of π_{rich}^0 free of γ_{dir} , the $v_2^{\gamma_{dir}}$ is given by:

$$v_2^{\gamma_{dir}} = \frac{v_2^{\gamma_{rich}} - \mathcal{R}v_2^{\pi_{rich}^0}}{1 - \mathcal{R}}, \quad (3)$$

where $\mathcal{R} = \frac{N^{\pi_{rich}^0}}{N^{\gamma_{rich}}}$, and the numbers of π_{rich}^0 and γ_{rich} triggers are represented by $N^{\pi_{rich}^0}$ and $N^{\gamma_{rich}}$ respectively. Although the \mathcal{R} quantity approximates all background triggers in the γ_{rich} sample to the measured π_{rich}^0 triggers, all background to γ_{dir} is subtracted assuming that all background triggers have the same correlation function as the π_{rich}^0 sample [5]. The value of \mathcal{R} is measured in [5] and found to be $\sim 30\%$ in central Au+Au. In Eq. 3 all background sources for γ_{dir} are assumed to have the same v_2 as the measured π^0 .

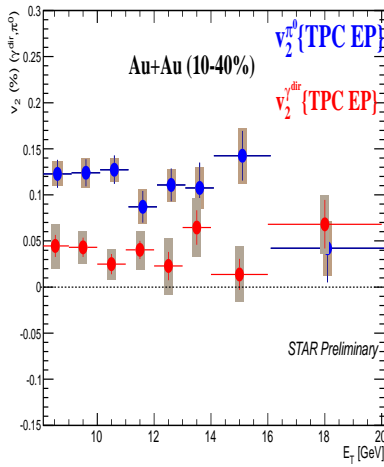


Figure 1. v_2 of π^0 , and γ_{dir} in 10-40% centrality of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using TPC. Boxes show the systematic errors.

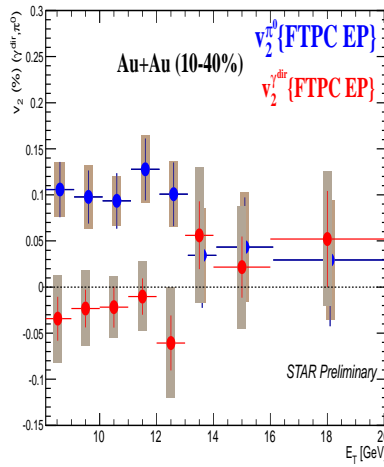


Figure 2. v_2 of π^0 , and γ_{dir} in 10-40% centrality of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using FTPC. Boxes show the systematic errors.

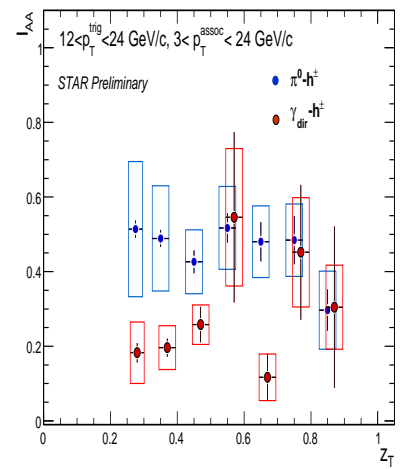


Figure 3. The z_T dependence of I_{AA} for γ_{dir} and π^0 triggers in Au+Au 0-10% centrality. Boxes show the systematic errors.

Figures 1 and 2 show the $v_2^{\pi^0}$ and $v_2^{\gamma_{dir}}$ for ($8 < p_T^{dir} < 20$ GeV/c) from Au+Au data set of Run 2011 using the TPC ($|\eta| < 1$) and FTPC ($2.4 < |\eta| < 4.0$). The results of Fig. 1 are consistent with those from different STAR data set of Run 2007 [13], and the results of Fig. 2 agree with other measurements [14, 15]. While using the FTPC in determining the event plane (Fig. 2) the $v_2^{\gamma_{dir}}$ is consistent with zero. Assuming the dominant source of direct photons is prompt hard production, the zero value implies no remaining bias in the event-plane determination. Accordingly, the measured value of $v_2^{\pi^0}$ would be the effect of path-length dependent energy loss.

2.6. Extraction of γ_{dir} associated yields

Assuming zero near-side yield for γ_{dir} triggers and a sample of π_{rich}^0 free of γ_{dir} , the away-side yield of hadrons correlated with the γ_{dir} is extracted as

$$Y_{\gamma_{dir}+h} = \frac{Y_{\gamma_{rich}+h}^a - \mathcal{R}Y_{\pi_{rich}^0+h}^a}{1 - \mathcal{R}},$$

$$\text{where } \mathcal{R} = \frac{N^{\pi_{rich}^0}}{N^{\gamma_{rich}}} = \frac{Y_{\gamma_{rich}+h}^n}{Y_{\pi_{rich}^0+h}^n}, \quad \text{and } 1 - \mathcal{R} = \frac{N^{\gamma_{dir}}}{N^{\gamma_{rich}}}. \quad (4)$$

Here, $Y_{\gamma_{rich}+h}^{a(n)}$ and $Y_{\pi_{rich}^0+h}^{a(n)}$ are the away (near)-side yields of associated particles per γ_{rich} and π_{rich}^0 triggers, respectively. The ratio \mathcal{R} is equivalent to the fraction of “background” triggers in the γ_{rich} trigger sample, and $N^{\gamma_{dir}}$ and $N^{\gamma_{rich}}$ are the

numbers of γ_{dir} and γ_{rich} triggers, respectively. The value of \mathcal{R} is found to be $\sim 55\%$ in p+p and decreases to $\sim 30\%$ in central Au+Au with little dependence on p_T^{trig} . All background to γ_{dir} is subtracted with the assumption that the background triggers have the same correlation function as the π_{rich}^0 sample.

In order to quantify the away-side suppression, we calculate the quantity I_{AA} , which is defined as the ratio of the integrated yield of the away-side associated particles per trigger particle in Au+Au to that in p+p collisions. The values of $I_{AA}^{\gamma_{dir}-h^\pm}$ and $I_{AA}^{\pi^0-h^\pm}$, as shown in Fig. 3, are z_T ($z_T = p_T^{assoc}/p_T^{trig}$) independent in agreement with results of [5] where the recoiled parton from γ_{dir} and π^0 experience constant fractional energy loss in the QCD medium. It is also observed that the charged hadron spectra recoiled from γ_{dir} show unexpectedly more suppression than those recoiled from π^0 ($I_{AA}^{\gamma_{dir}-h^\pm} < I_{AA}^{\pi^0-h^\pm}$) within the covered kinematics range $12 < p_T^{\gamma_{dir}, \pi^0} < 24$ GeV/c and $3 < p_T^{assoc} < 24$ GeV/c.

3. Conclusions

The STAR experiment has reported the first $v_2^{\gamma_{dir}}$ at high- p_T ($8 < p_T^{\gamma_{dir}} < 20$ GeV/c), and explored new kinematic range ($12 < p_T^{\gamma_{dir}, \pi^0} < 24$ GeV/c) and ($3 < p_T^{assoc} < 24$ GeV/c) for I_{AA} measurements of $\gamma_{dir} - h$ correlations at $\sqrt{s_{NN}} = 200$ GeV. Using the mid-rapidity detectors in determining the event plane, the measured value of $v_2^{\gamma_{dir}}$ is non-zero, and is probably due to biases in the event-plane determination. Using the forward detectors in determining the event plane could eliminate remaining biases, and the measured $v_2^{\gamma_{dir}}$ is consistent with zero. The zero value of $v_2^{\gamma_{dir}}$ suggests a negligible contribution of jet-medium photons [17], and negligible effects of γ_{frag} [16] on the $v_2^{\gamma_{dir}}$ over the covered kinematics range. The measured finite value of $v_2^{\pi^0}$, using the forward detectors in determining the event plane, is apparently due to the path-length dependence of energy loss. The $\gamma_{dir} - h$ correlation results indicate that the associated charged hadron spectra recoiled from γ_{dir} show more suppression than those recoiled from π^0 ($I_{AA}^{\gamma_{dir}-h^\pm} < I_{AA}^{\pi^0-h^\pm}$) within the covered kinematic range, in contrast to the theoretical predictions [18]. The disagreement with the theoretical expectations may indicate that the lost energy is distributed to lower p_T of the associated particles in the case of a γ_{dir} trigger than a π^0 trigger. To further test this, one must explore the region of low p_T^{assoc} and z_T .

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